

Formation Mechanisms for Spirals in Barred Galaxies

E.V.Polyachenko and V.L.Polyachenko^{*}

Institute of Astronomy, Moscow 109017, Russia

ABSTRACT

We consider a scenario of formation of the spiral structure in barred galaxies. This scenario includes the new non-resonant mechanism of elongation of spirals, due to the characteristic behaviour of the gravitational potential beyond the principal spiral arms.

The following scheme is considered. At first a bar forms in the centre (e.g., as a result of an instability). The bar induces the spiral resonance responses off the bar ends. If these primary (principal) spirals are strong enough, they initiate the formation of the nearly circular spirals that elongate the primary spirals. The process of elongation can be repeated.

To describe the response of the galactic disk, one can assume the model of the disk with circular orbits. The linearized hydrodynamical equations give a relation for perturbations of the surface density $\sigma(r)$ and the potential $\Phi(r)$ (e.g., see Fridman & Polyachenko, 1984):

$$\sigma(r) = -\frac{1}{r} \frac{d}{dr} \left(r \varepsilon \frac{d\Phi}{dr} \right) + \frac{4}{r^2} \varepsilon \Phi + \frac{4}{r \omega_*} \Phi \frac{d}{dr} (\varepsilon \Omega). \quad (1)$$

Here we assumed that all perturbations $\sim \exp(-i\omega t + 2i\varphi)$, t is time, $\omega = 2\Omega_p + i\gamma$, Ω_p is the pattern speed, γ is the growth rate, $\varepsilon(r) = \sigma_0(r)/(\omega_*^2 - \kappa^2)$, $\sigma_0(r)$ is the unperturbed density, $\kappa^2 = 4\Omega^2 + r d\Omega^2/dr$, $\Omega(r)$ is the local angular velocity, $\omega_*(r) = \omega - 2\Omega(r)$.

The principal spirals constitute the response (1) to the bar potential $\Phi(r, \varphi) \sim r^{-n} \cos 2\varphi$ ($n > 0$; the bar is fixed vertically). At the outer inner Lindblad resonance (outer ILR; slow bars), Eq. (1) leads to a trailing spiral with the maximum length in azimuth equal to π . If the bar were within the inner ILR, the spiral structure began with the leading primary spirals (Pasha & Polyachenko, 1994).

For the bar that ends near the corotation $r = r_c$ (CR; fast bars), Eq. (1) gives the following equation for the resonance spiral (if $|\sigma'_0/\sigma_0| > |\Omega'/\Omega|$):

$$\varphi = \varphi_c(r) + \pi/2, \quad \tan 2\varphi_c(r) = -\frac{\gamma}{2\Omega'_c(r - r_c)}, \quad (2)$$

where $\Omega'_c = d\Omega/dr|_{r_c}$. This is a trailing spiral off the bar with the maximum length equal to $\pi/2$. So the length of the principal spiral arms can differ slow and fast bars: on average, the latter should be twice shorter than the former.

Fig. 1a shows the barred galaxy NGC 1365, along with the overlaid Fourier harmonic of the light distribution that corresponds to the predominant two-armed symmetry. The surface density of the material σ_2 can be written as $\sigma_2(r, \varphi) = \text{Re}[\sigma(r) \exp(2i\varphi)] = A(r) \cos[2\varphi - F(r)]$. Functions $A(r)$ and $F(r)$ are displayed in Fig. 1b. As is seen, the spiral arms consist of two clearly different parts: (1) fairly open *principal arms* off the bar; (2) adjacent nearly circular *quarter-turn spirals*, each being terminated by radially-

aligned oscillations made of short alternating leading and trailing spirals. These two parts differ essentially both in amplitude and pitch angle.

The very similar spirals can be observed elsewhere, for example, in the normal galaxies NGC 3631 and NGC 157 in which the spirals exist not only in the outer region but also in the central region.

This phenomenon is in fact quite common. The quarter-turn spirals are essentially the response of the galactic disk to the gravitational potential of the principal arms, when the potential reveals the characteristic behaviour (see dotted lines in Fig. 2). This behaviour can be described as a transition between spiral and multipole regimes.

The potential $\Phi_2(r, \varphi)$ tends to the quadrupole form well away from the spirals: $\Phi_2(r, \varphi) \rightarrow r^{-3} \cos 2(\varphi - \varphi_0)$ ($\varphi_0 = \text{const}$). Hence $\Phi_2(r, \varphi) = \text{Re}[\Phi(r) \exp(2i\varphi)]$ has non-spiral asymptotic behaviour. In practice, the potential Φ_2 transforms into the multipole form $\Phi_2(r, \varphi) \sim r^{-n} \cos 2(\varphi - \varphi_0)$ ($n = -d \ln \Phi / d \ln r$, $n \rightarrow 3$ at sufficiently large radii) well before the quadrupole regime. It occurs in the very narrow interval of radii just beyond the principal spiral. Due to fast radial variation in the spiral region as well as in the transition domain, one can neglect all but one term in (1): $\sigma(r) \cong -\varepsilon d^2 \Phi / dr^2$. As a rule, the spirals end within the region, where $\omega_*^2 < \kappa^2$. Hence $\varepsilon < 0$, so $\sigma(r) \propto \Phi''$.

This result is confirmed by Fig. 2, which shows the loci of responses, which are calculated by the formula (1), to the potential produced by the principal arms. The spiral-like potential leads to $\Phi'' \sim -k^2 \Phi$ ($k = F'$) while $\Phi'' \sim +n(n+1)\Phi$ in the multipole regime. It means that the complex phase of the function $B(r)$, which is the proportional coefficient between the density and the potential, $\sigma(r) = B(r)\Phi(r)$, varies from $-\pi$ in the spiral region to 0 in the multipole region. Accordingly, the two-armed response has the angular length equal to $\pi/2$ since the phase change ΔF is twice as much as the turn angle $\Delta\varphi$ of the two-armed spiral, $\Delta F = 2\Delta\varphi$, and here $\Delta F = \pi$.

This research has made use of the NASA/ IPAC Extragalactic Database (NED). The work was supported in part by grants of RBRF.

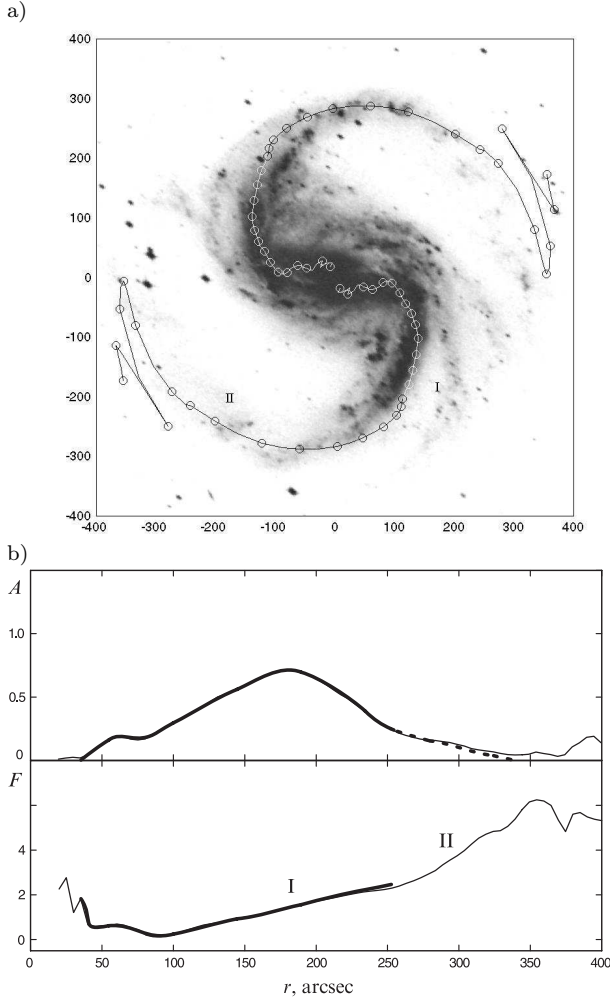


Figure 1. (a) Deprojected image of the galaxy NGC 1365, along with the overlaid two-armed Fourier harmonic of the light (blue) distribution. The image is obtained from NED archive. I – the principal spirals; II – the quarter-turn spirals. (b) Amplitude $A(r)$ and phase $F(r)$ of the Fourier harmonic in Fig. 1a. Thick lines show the smoothed functions used for calculations of the galactic disk response (cf. Fig. 2).

REFERENCES

- Fridman, A.M. & Polyachenko, V.L., 1984. *Physics of Gravitating Systems*, Springer-Verlag, New York.
Pasha, I.I. & Polyachenko, V.L., 1994. *Mon. Not. R. astr. Soc.*, **266**, 92.

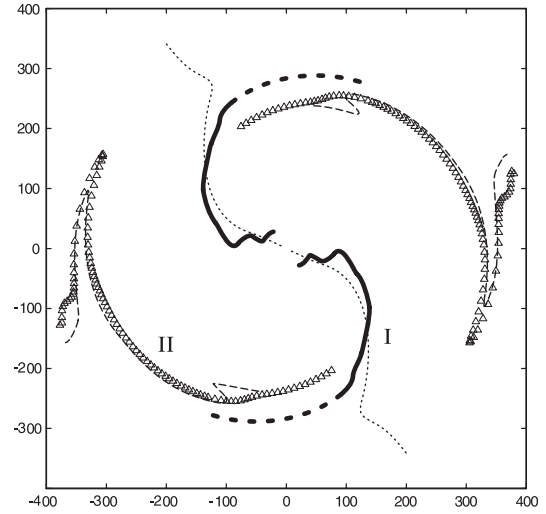


Figure 2. Response of the galactic disk of NGC 1365 (triangles, II) to the gravity of the principal spirals (thick solid curves, I). As is seen, this response and the quarter-turn spirals in Fig. 1 (a) are very similar. Dotted lines are used for the curve of minima of the two-armed potential $\Phi_2(r, \varphi)$. Dashed lines show maxima of the function $\text{Re}[\exp(2i\varphi) \cdot \Phi'']$. Qualitatively, the patterns of the quarter-turn spirals do not depend on particular values of disk and spiral wave parameters. In particular, these patterns are insensitive to a specific band used (although for other bands the amplitude of the two-armed harmonic can fall in the central region slower).